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Title: Piezoelectret Foam-Based Vibration Energy Harvester for Low-Power Energy Generation

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Piezoelectret Foam-Based Vibration Energy Harvester for Low-Power Energy Generation

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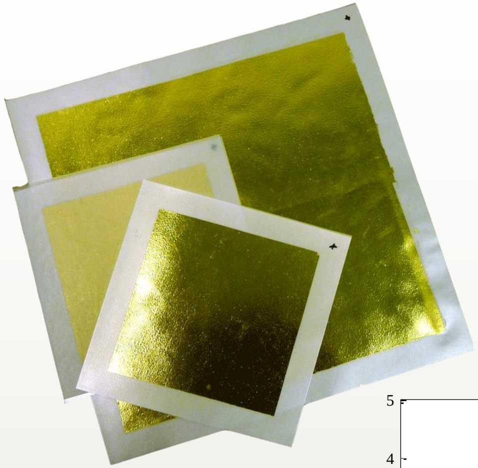
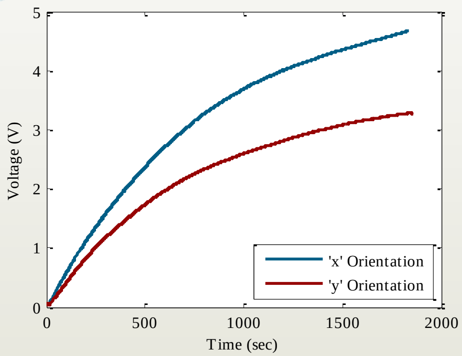
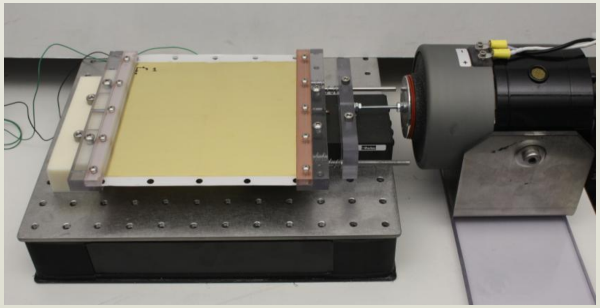
Outline

- **Introduction**
  - Motivation for current research
  - Introduction to piezoelectret foams
  - Previous work on piezoelectret foams
- **Material Characterization**
  - Mechanical tensile testing
  - Electromechanical d_{33} measurements
- **Energy Harvesting Experimentation**
  - Dynamic characterization
  - Energy harvesting ability
    - Charge profiles
    - Orthogonality investigation
- **Conclusions**



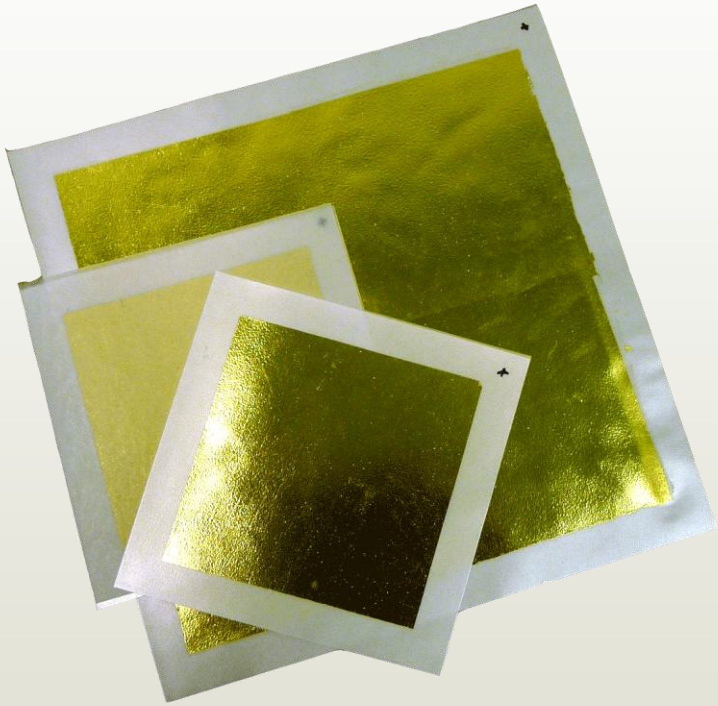




Motivation for Current Research

Piezoelectret foams present a novel material for potential energy harvesting applications. They hold promise for high mechanical compliance and relatively large piezoelectric response.

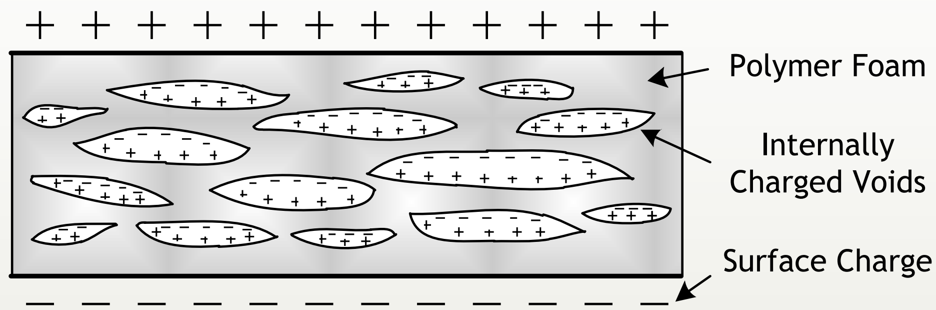
- Few studies on energy harvesting capability of piezoelectret foams in direct compression
- Most consider electrostatic harvesting with electrets (parallel plate capacitor-type design)
- Compliant vibration harvesters offer advantages in environments with large deflections or attaching to curved surfaces
- Published d_{33} value up to 7x larger than PVDF

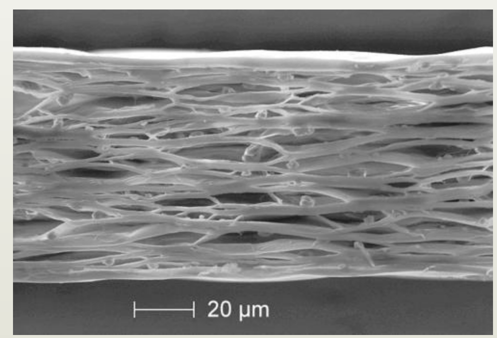


Introduction to Piezoelectret Foams

Piezoelectret foam is a cellular polymer electret material with internally charged voids that form “macroscopic” dipoles allowing piezoelectric behavior

- **Formed using a biaxial stretching process to create voids**
- **Corona charging causes Paschen breakdown of the gas in the air voids, permanently placing charge on the void surfaces**
- **Internally charged voids create “macroscopic diploes” allowing piezoelectric activity**





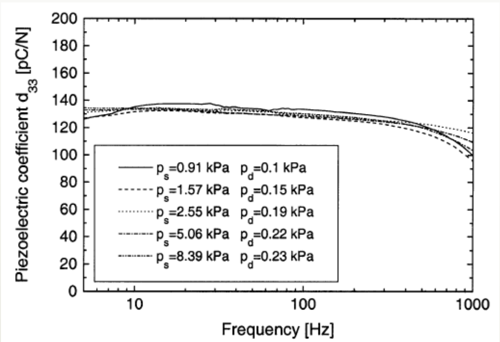
Sessler and Hillenbrand, *Applied Physics Letters*, 1999

Unlike ferroelectrics, ferroelectrets operate based on thickness changes in the air voids (like a parallel plate capacitor).

Previous Work on Piezoelectret Foam

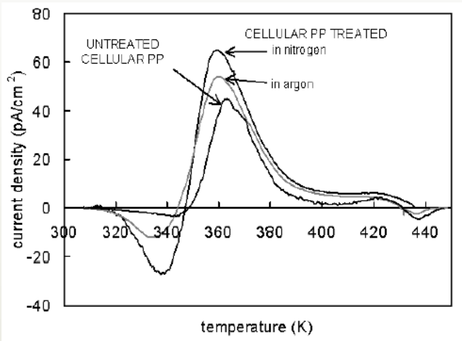
Development began in 1980s at Tampere University of Technology in Finland. Most early work has focused on material characterization and modeling.

Dynamic d_{33} Measurements



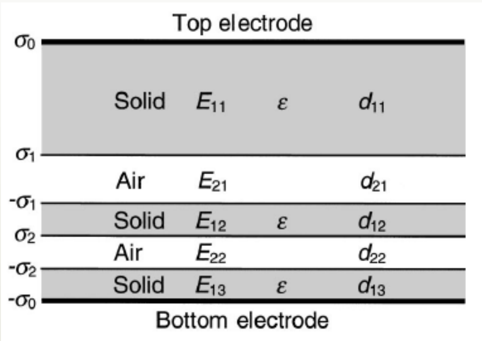
Hillenbrand and Sessler, *IEEE Trans. On Dielec. And Elec. Insl.* 2004

Effects of Gas in Voids



Paajanen, et. al, Journal of Physics D: Applied Physics, 2001

Layered Model



$$t_{33} = \frac{\Delta\sigma_0}{p} = \frac{\epsilon d}{Y}\frac{d_1 \sum_j d_{2j}\sigma_j}{d_2(d_1+\epsilon d_2)^2}$$

Sessler and Hillenbrand, *Applied Physics Letters*, 1999

Suggested Applications:

Sensing

- Touch sensors
- Floor sensors
- Guitar pickups
- Microphones

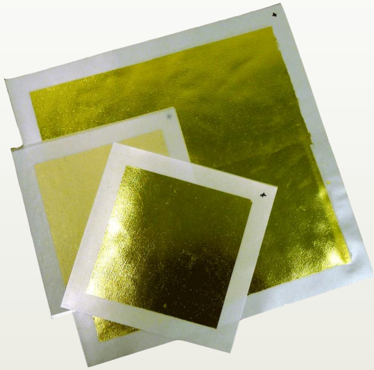
Actuation

- Loudspeakers

Mechanical Tensile Testing - Materials and Setup

Tensile testing is performed on various samples to quantify the modulus of elasticity and tensile strength of the material.

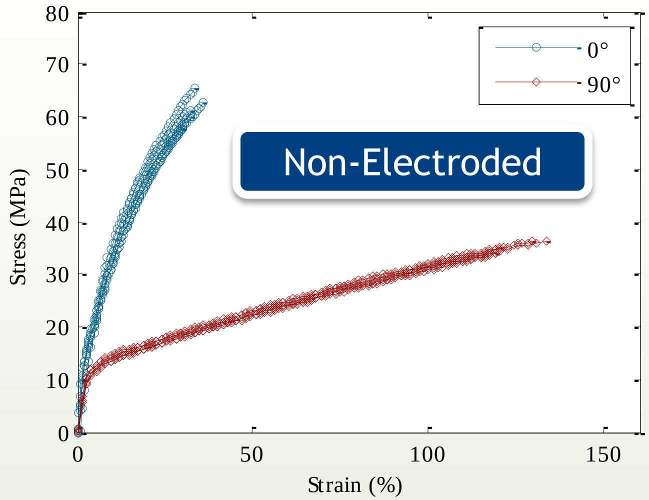
Emfit HS-04 film

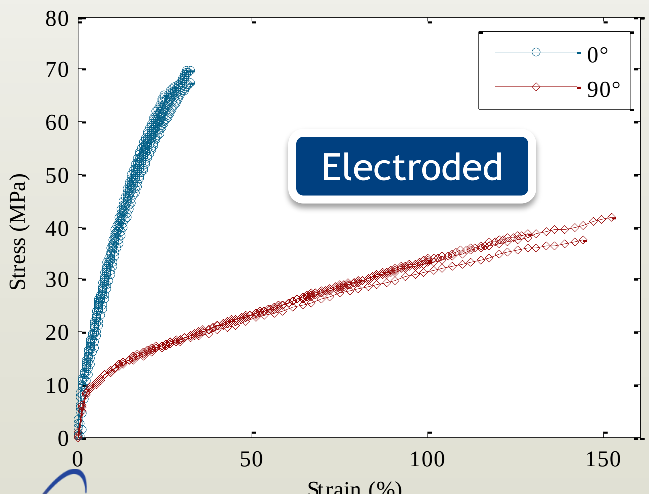


Property	Value
Operating Temperature	-20 °C to +50 °C
Thickness	80-100 μm
Sensitivity (d_{33})	25-250 pC/N
Young's Modulus (thickness direction)	0.5 MPa
Operating Force Range	>100 N/cm^2

- **ASTM D882-10 (Tensile Properties of Thin Plastic Sheeting)**
  - Uniform samples
  - Sample width: between 5.0 mm and 25.4 mm
  - Sample length: between 100 mm and 250 mm
  - Aspect ratio (width to thickness): ≥ 8
  - Strain rate: 0.1 mm/mm·min
- **Uniform samples created (9.5mm x 76.2mm) with and without electrodes**

Tensile Testing - Results





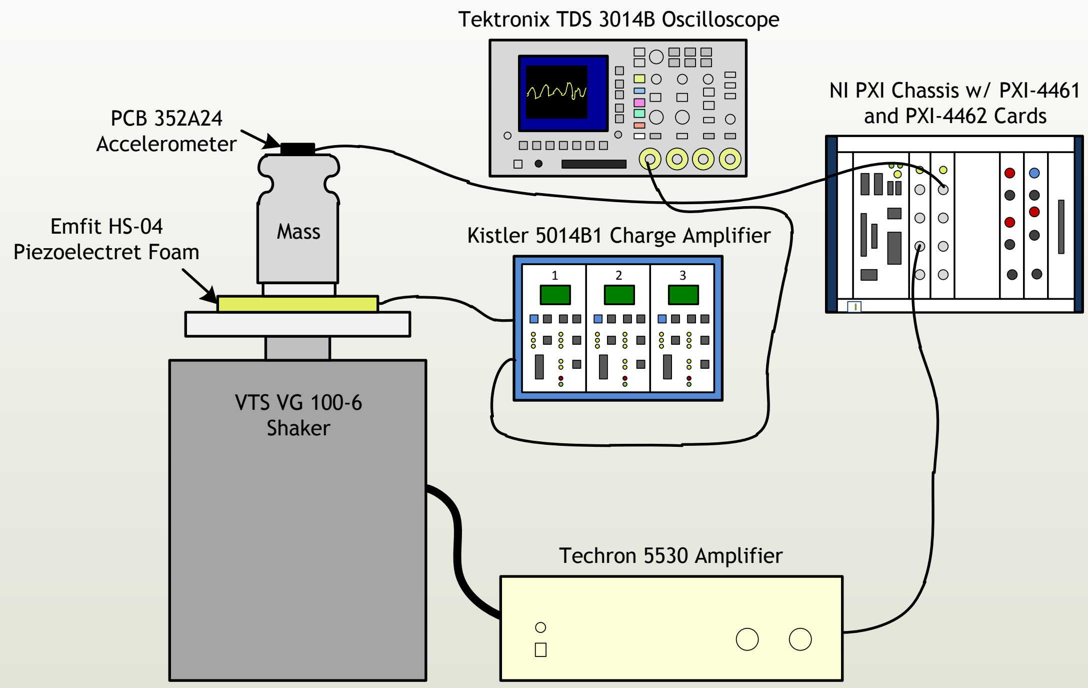
Property	Non-Electroded Samples		Electroded Samples	
	0°	90°	0°	90°
Young's Modulus (Mpa)	990	515	940	475
Tensile Strength (Mpa)	63	36	68	40

- Anisotropic (bi-axial stretching)
- Large strains (35-150% to failure)
- Electroded samples have slightly lower modulus and slightly higher tensile strength
- Young's modulus in length direction is 3 orders of magnitude larger than thickness direction

Electromechanical Testing - Setup

Measurements of the dynamic d_{33} coefficient are performed and compared to values published in the literature.

- **Dynamic testing is performed using shaker excitation**
- **d_{33} measured over a range of frequencies by holding acceleration constant while sweeping**
- **Various combinations of mass and acceleration tested (various static and dynamic forces)**



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Electromechanical Testing - Theory

The sample is loaded by both static and dynamic forces. These forces (pressures) can be used to calculate d_{33} (only the dynamic force is needed).

Static force/pressure

$$f_s = mg \quad \Rightarrow \quad p_s = \frac{mg}{A}$$

Dynamic force/pressure

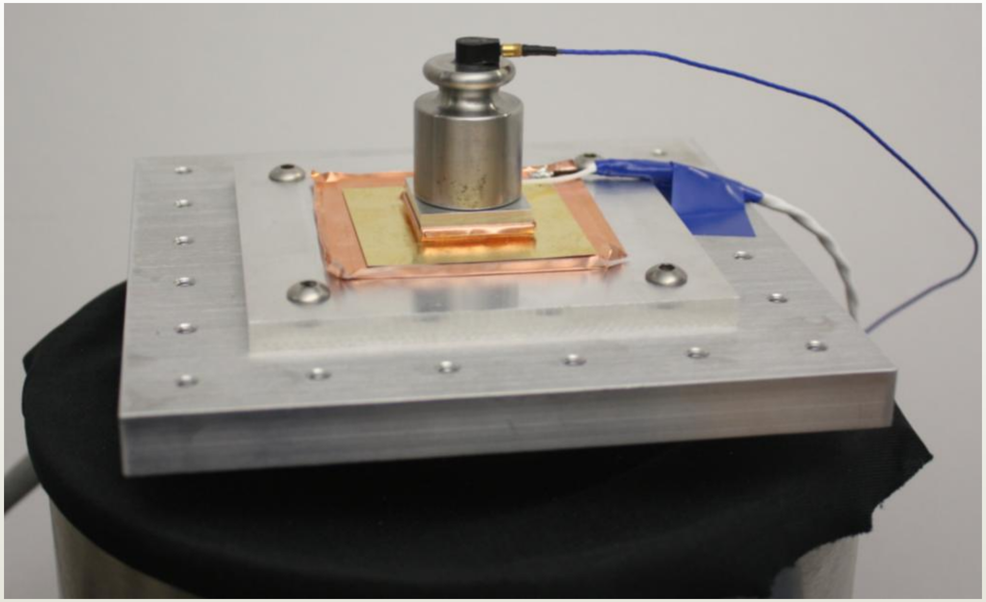
$$f_d = ma \quad \Rightarrow \quad p_d = \frac{ma}{A}$$

Total pressure (sinusoidal excitation)

$$p(t) = p_s + p_d \cos(\omega t)$$

d_{33} is calculated using dynamic pressure

$$d_{33} = \frac{C}{f_d} = \frac{C}{ma}\left(\frac{pC}{N}\right)$$



$m =$ mass

$g =$ gravity

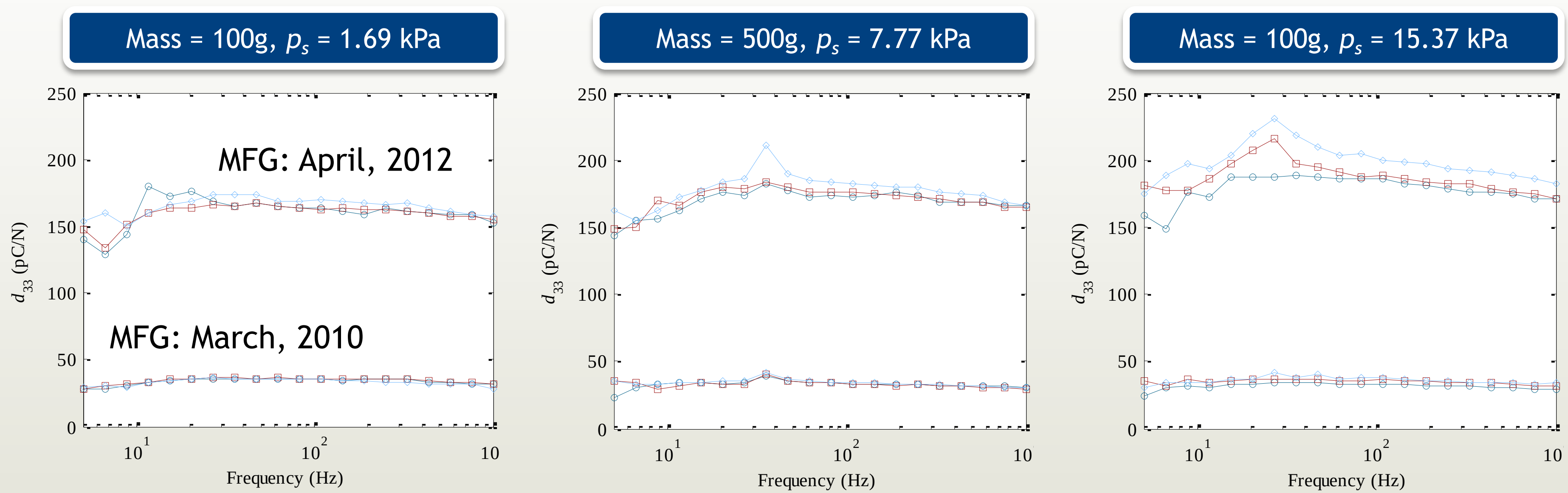
$a =$ acceleration

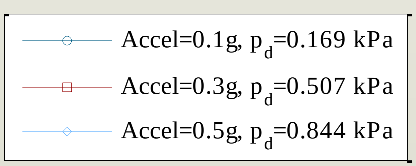
$A =$ area

$C =$ charge

Electromechanical Testing - Results

d_{33} is relatively linear across the range from 5 Hz – 1 kHz (encompassing most macro-scale vibration energy harvesting regimes). The age of the samples may affect the d_{33} measurement.





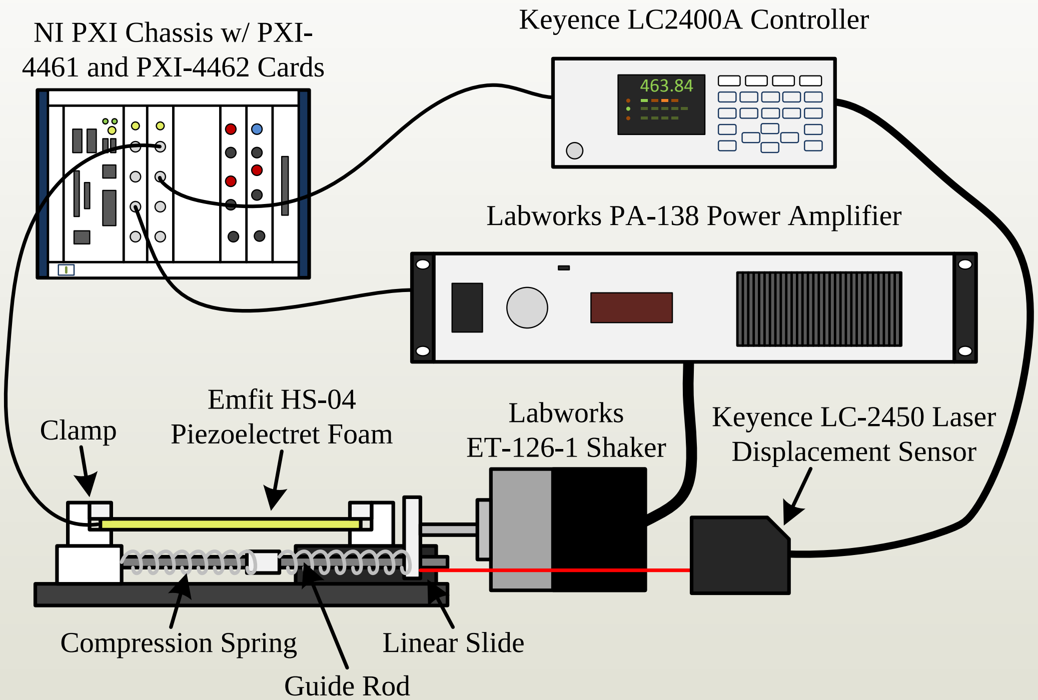
Measured: $d_{33} \approx$ 35 pC/N (March 2010)

$d_{33} \approx$ 175 pC/N (April 2012)

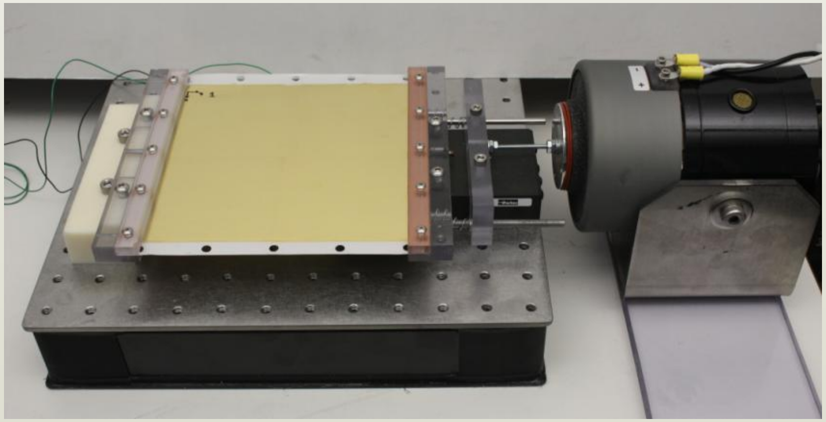
Manufacturer Specification: $d_{33} \approx$ 25-250 pC/N

Energy Harvesting - Experimental Setup

The ability of ferroelectret foam to harvest vibration energy is explored by sinusoidally exciting a sample along the length direction and using the energy generated to charge a capacitor



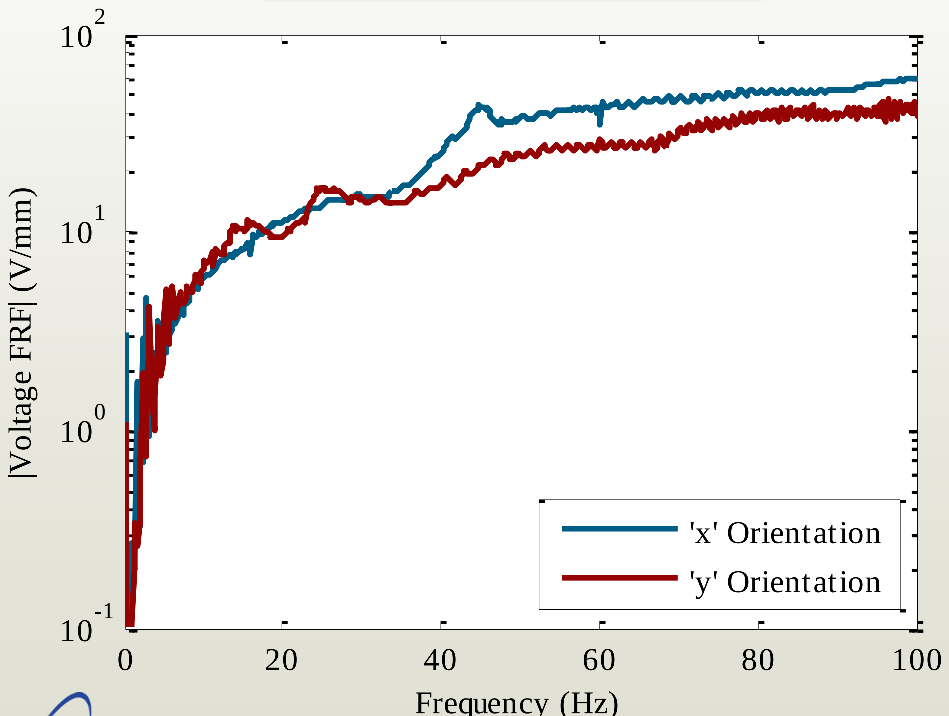
- **Sample Size: 15.24 x 15.24 cm**
- **MFG Date: April, 2012**
- **Pre-tensioning fixture**
- **Simple bridge rectifier circuit used to charge 1mF capacitor**



Energy Harvesting - Dynamic Characterization

Electromechanical Frequency Response Functions (FRFs) are measured in order to determine the dynamic characteristics of the system. Both “x” and “y” orientations are explored (recall anisotropy).

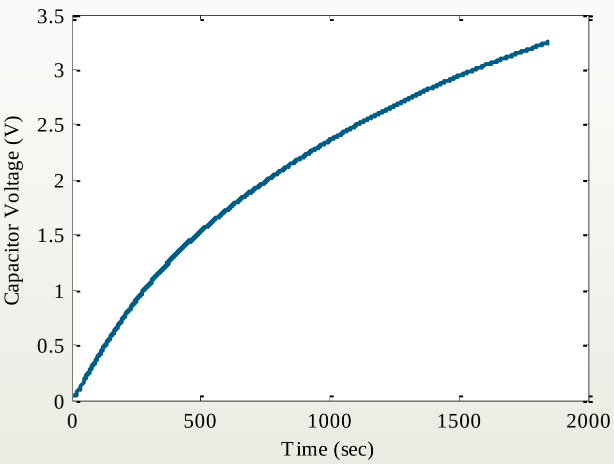
Voltage-to-Displacement FRF

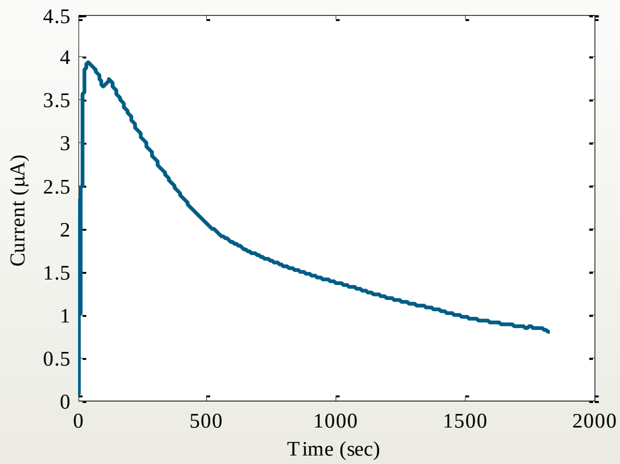


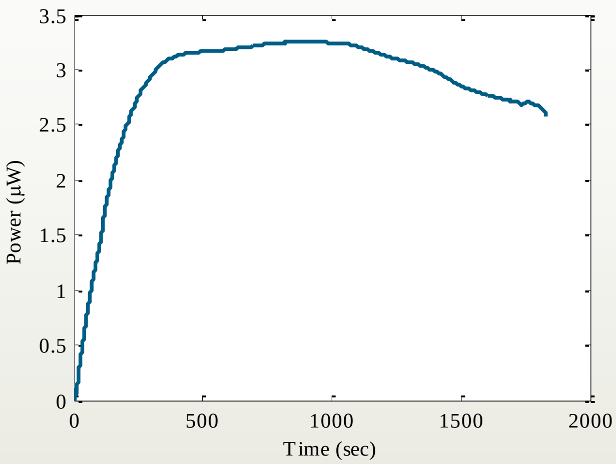
- FRFs measured using a Brüel & Kjær Photon dynamic signal analyzer using chirp excitation
- Voltage measured directly
- Displacement measured using Keyence laser displacement system
- “x” orientation slightly more sensitive

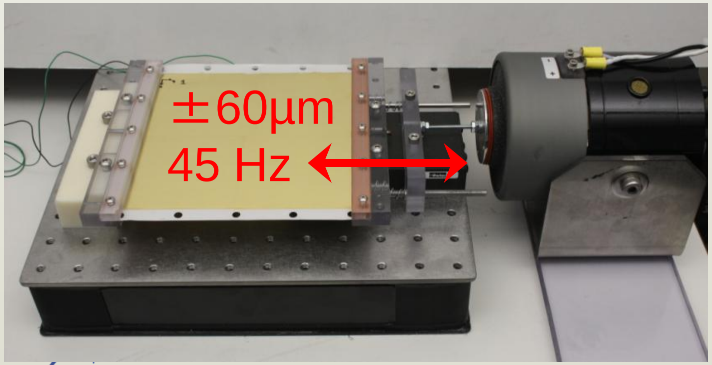
Energy Harvesting Results

Harmonic excitation of pre-tensioned sample shows the ability of the piezoelectret foam to charge a storage capacitor.





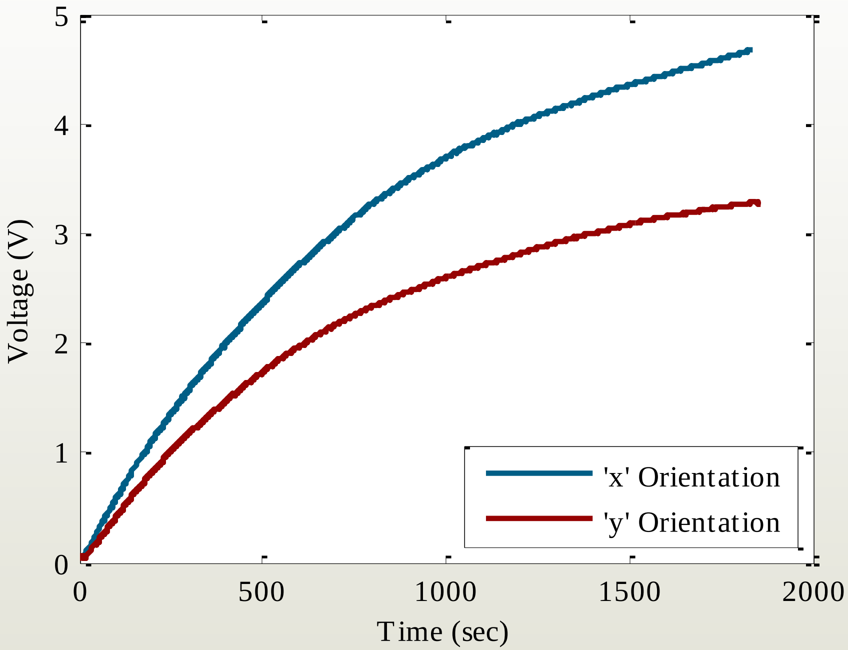


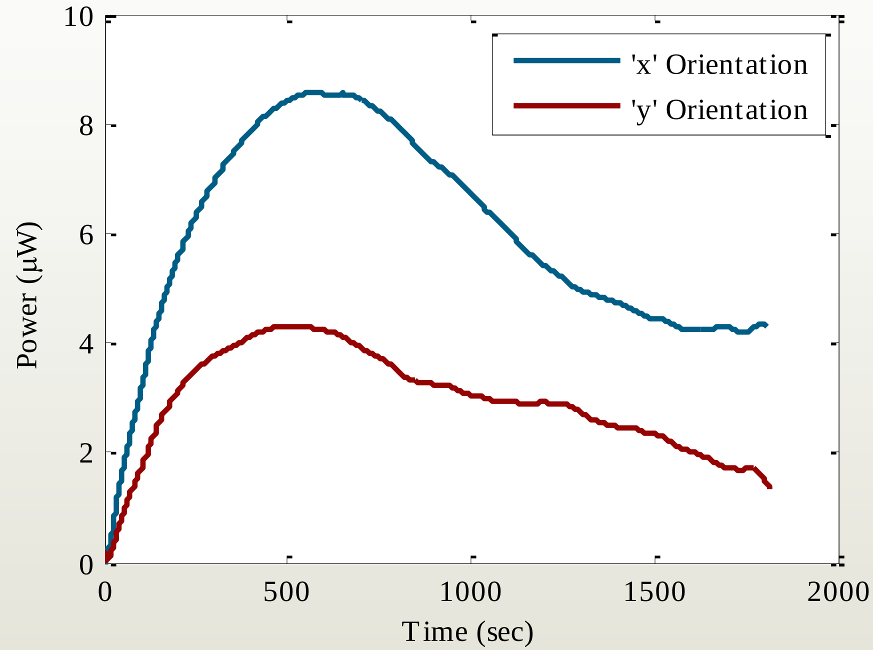


- 30 min of excitation results in a voltage of 3.24 V on the capacitor
- Average power output of 2.8 μW

Energy Harvesting Results

Comparison of the "x" and "y" orientations for energy harvesting confirm the higher sensitivity of the preferred "x" orientation.



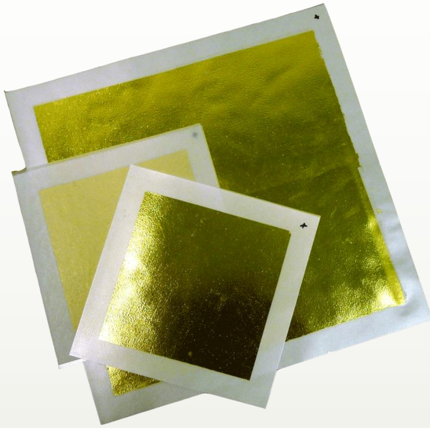


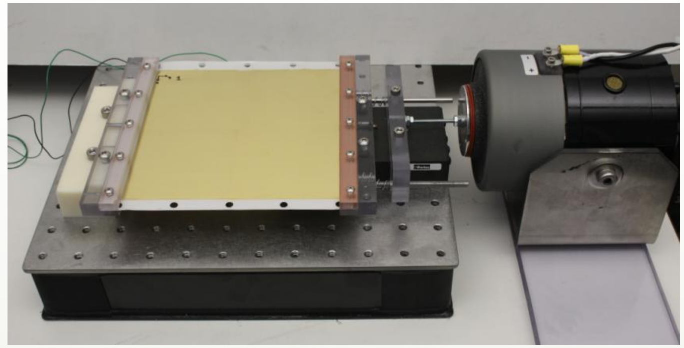
- **60 Hz excitation (off resonance for both orientations)**
- **Power output levels are comparable to other polymer piezoelectrics (i.e. PVDF)**

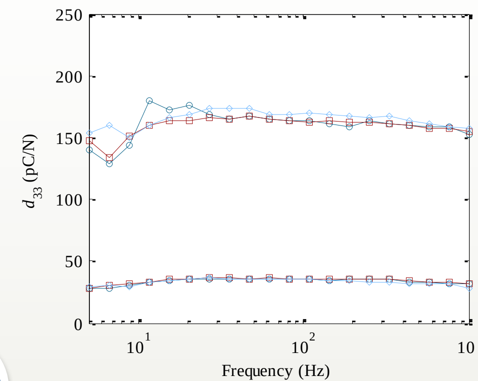
Conclusions

- **Cellular polypropylene ferroelectret foam presents a novel material with energy harvesting potential**
- **Mechanical Properties:**
  - The material is anisotropic (based on 0º and 90º samples).
  - Y ≈ 0.4-1 GPa, Tensile Strength ≈ 30-60 MPa.
  - Electrodes have slight effect on Young's modulus and tensile strength.
- **Electromechanical Properties:**
  - Approximately constant d_{33} ≈ 35/200 pC/N for 5 Hz – 1 kHz test range.
  - Aged samples appear to have significant decrease in d_{33}.
  - Future testing should investigate aging effects.
- **Energy Harvesting Feasibility:**
  - Using a large (≈ 15 cm x 15 cm) sample excited along the length direction, piezoelectret foam is able to charge a 1 mF cap to above 4 V in 30 min.
  - Average power of ≈ 5 µW is comparable to other polymer-based piezoelectrics.

Thank You







QUESTIONS??